

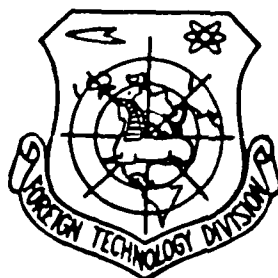
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ULTRA-HIGH-PRECISION MACHINING TECHNIQUES: APPLICATIONS AND CURRENT STATUS

by

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ULTRA-HIGH-PRECISION MACHINING TECHNIQUES: APPLICATIONS AND CURRENT STATUS

Xiao Xin

The article describes in general the applications of ultra-high-precision machining techniques in present-day high-technology product manufacturing. Moreover, a general account is given of principal methods and means of implementing ultra-high-precision machining as well as the developmental status of ultra-high-precision machining in today's China and abroad.

Ultra-high-precision machining lacks any clear-cut definition. Generally, this means machining at the highest precision at the present time. Therefore, ultra-high-precision machining reflects the times. Generally, ultra-high-precision machining indicates machining techniques within 0.1 micrometer of absolute machining precision, and with Ra 0.01 micrometer as the surface coarseness, as well as the ratio between the machining allowance and machined dimension being 10^{-6} .

Applications and Importance of Ultra-High-Precision Machining Technique

Present-day ultra-high-precision machining techniques are mainly applied in aerospace, aeronautics, precision instruments

and meters, as well as the computer and optical industries. For example, the planarity of magnetic disks used in computers is required to be between 0.1 and 0.5 micrometer and the surface coarseness be between Ra 0.003 and 0.05 micrometer. For X-ray astronomical telescopes used in studying celestial bodies their largest diameter is more than 1 m and their length longer than 0.6 m; however, the requirements on dimensional precision are 1 micrometer and surface coarseness Ra 0.05 micrometer. For optical parts used for ultraviolet rays and X-rays, surface coarseness is required to be Ra 0.001 micrometer. The spherical roundness of inner and outer supports for gas-lubricated gyroscopes used in conventional inertial instruments or meters is between 0.2 and 0.6 micrometer; the dimensional precision is 0.6 micrometer; and the surface coarseness is between Ra 0.012 and 0.05 micrometer. However, the planarity of plane reflecting lenses of a laser gyroscope is only 0.03 micrometer, and surface coarseness Ra is less than 0.012 micrometer. In addition, there are reflecting mirrors used for laser fusion reactions, multifaceted prisms of graduated precision for inspecting rotary work platforms, selenium drums in copiers, magnetic heads and optical disks of video recorders, and silicon chips in large-scale integrated circuits of a computer have very high requirements on surface coarseness and dimensional precision.

In the absence of ultra-high-precision machining techniques, the above-mentioned steady precision requirements are beyond reach, therefore these products could never be realized. Thus, the following areas would be affected: national scientific and technical developments, quality of defense equipment, and the level of industrial development. Hence, all governments worldwide pay close attention to research and development of ultra-high-precision machining techniques.

Methods and Means of Implementing Precision Machining

There are principles of maternal parentage and creativity in attaining workpiece machining precision. The so-called principle of maternal parentage states that errors of machine tool transmission chain and geometry with respect to workpiece machining will be transmitted to the workpiece in some form. Hence, workpiece precision will imitate machine tool precision with lower precision in the workpieces. The so-called creativity principle states that lower-precision machine tools can use a special implement and technical means in order to machine workpieces with one level higher precision (direct precision enhancement), or alternatively lower-precision-level machine tool equipment can produce a new generation of machine tools with precision level higher than the workpiece precision by using special fixtures and technical means for batch production of higher-precision parts (indirect precision enhancement). By correctly applying two creativity machining principles of direct and indirect precision enhancement, precision machining can be raised to ultra-high-precision machining.

Generally, in batch production always the principle of maternal parentage is applied to attain workpiece precision and to ensure stable machining quality. Only in the case of trial manufacture of limited quantities of workpieces can the machining principle of direct precision enhancement be used to attain high workpiece precision. Nonetheless, the error compensation technique is involved in developments of modern science and technology as well as progress in software scientific technology. In other words, machine tools of lower-precision-levels are used and computer-controlled systems are employed to apply overall error compensation according to the on-line measurement error of a workpiece; therefore, the machining precision of the machine tool can undergo major improvements, thus implementing a higher precision level of workpiece machining.

At the present time, in addition to traditional milling and grinding for implementing ultra-high-precision machining in the machine shop practice, mainly natural diamonds are used for cutting tools for ultra-precision lathe work, boring, and milling. Besides, for structural materials with steady higher strength, higher hardness, and higher toughness, usually special machining is required, such as electric discharge machining and electric erosion grinding; these techniques need to be promoted to ultra-high-precision machining with major progress. The dimensional precision and surface coarseness of this machining are close to or reach the requirements of ultra-high-precision machining, becoming an indispensable technical means for implementing ultra-high-precision machining.

Current Developmental Status of Ultra-High-Precision Machining Techniques

The ultra-high-precision machining is a comprehensive set of techniques, requiring the consideration of high-precision machine tools and equipment, precision instruments and meters, control apparatus, optimal quality workpiece and materials, cutting tools, as well as techniques and environmental cleanliness.

1. Machine tool for ultra-high-precision machining

First, the ultra-high-precision machining machine tool should ensure the attainment of the prescribed high precision and ensure operational stability and high reliability. Next come improvements in machining efficiency and cost reduction. The key components of machine tool structure for ultra-high-precision machining are the main shaft system, guide rail, and drive system. The present main shaft system adopts one of the two following types: air-static pressure shaft system and hydraulic static pressure shaft system. The air-static shaft system is low in rigidity, but the gap between the shaft bearing can be very

small, capable of attaining relatively higher rotary precision. Because of air cooling, precision can be ensured even with long periods of operation. This shaft system can be used for ultra-high-precision machine tools with relatively small cutting force. The hydraulic static shaft system is high in rigidity, but certain gaps should exist between shaft and bearing, thus easily making the system subject to thermal deformation. Hence, isothermal cooling should be employed for hydraulic static shaft systems in order to ensure stable precision in prolonged operational periods.

Mainly, two types of guide rails are used for ultra-high precision machine tools: hydrostatic pressure guide rails and air-static pressure guide rails (gas-lubricated). The hydrostatic pressure guide rail operates entirely in a state of pure fluid friction so that movements are steady, capable of damping vibration without creep and wear, and thus its bearing capacity is high. If isothermal hydraulic oil is used, thermal deformations of a machine tool can be reduced during its operation in order to maintain machining precision. The linear precision of gas-lubricated guide rails is high; at present, perforated graphite gas cushion pads are used for gas-lubricated guide rails. Thus, not only can this arrangement serve a protective function, but also enhance the gas film rigidity of gas-lubricated guide rails after the guide rail is dipped into some solution.

There are main shaft and feed drive systems. In a main shaft drive system, it is required to have pure torque transmission, thus with the two drive methods of eddy current electric machinery and hydraulic motors. The feed drive is a linear drive, generally in the form of a stepping motor--ball-bearing tap pair drive, hydraulic linear motor drive, and linear type induction servomotor drive.

Besides, precision positioning, alignment, instruments (and meters) with micro-displacement, and a control system are required for ultra-high-precision machine tools.

At the leading position in the world, the United States had the earliest development of ultra-high-precision machine tools. As early as 1961, a semispherical lathe was successfully developed in the United States; in addition, gas-lubricated hollow bearings with perforated graphite bushing were developed; the rotary precision of the main shaft is 0.125 micrometer.

In 1984, large diamond-tipped precision lathes were developed in the Lawrence Livermore Laboratory (LLL) in the United States; lubricating oil has a temperature control feature at 20 plus or minus 0.0025 °C; a flow of 1.5 m^3/min is used for maintaining isothermal machine tool operation, thus ensuring machining precision of the machine tool. The rectilinearity of the machine tool guide rail is 0.01 micrometer per meter, capable of cutting, grinding, and burnishing. Very large workpieces of 4-5 tons in weight and 2.1 meters in diameter can be machined with ultra-high-precision.

After the seventies, numerous types of ultra-high-precision machine tools were also developed in West European countries and in Japan; some factories in China also developed several kinds of ultra-high-precision machine tools.

2. Diamond-tipped ultra-high-precision cutters and grinding

In ultra-high-precision cutting, a very thin layer of metal less than 0.01 micrometers in thickness should be removed; therefore, the smaller the better for the radius ρ of the blade arc of the diamond-tipped cutter that is required. At present, the blade radius ρ used industrially can be as small as 0.01 to 0.02 micrometer in the United States, and 0.1 to 0.08 micrometer

in China. Since natural diamond is expensive, substitutes have always been sought for, such as polycrystalline cubic diamond and polycrystalline cubic boron nitride; however, these materials still are not suitable for use in ultra-high-precision machining. Monocrystalline cubic diamond and monocrystalline cubic boron nitride show promise; these materials can be used for ultra-high-precision machining of ferrous and nonferrous metals. Besides, the application of ion coating techniques is used to deposit thin layers of diamond on substrates of different tools with the expectation that they can be used in ultra-high-precision machining. These approaches will have a revolutionary impact on cutters for ultra-high-precision machining.

3. Ultra-high-precision measurement techniques

Ultra-high-precision measurement is indispensable to ultra-high-precision machining. At present, measurement precision is the highest for instruments using the optical wave interference method. In addition, electric measurement techniques (micrometers using electric inductance and capacitance) and gasdynamic measurement techniques have applications in the measurement of ultra-high-precision machining. The measurement precision of the optical wave interference comparison instruments is 0.02 micrometer. The measurement unit of a type of hybrid interference instrument is 0.0002 micrometer. By measuring surface coarseness with the optical waves multiple interference method, its sensitivity can be between 1 and 10 angstroms. The resolving power of a tunnel current probe is less than 1 nanometer. By using instruments based on the optical wave interference method for measuring workpiece roundness and sphericity, a precision between 0.001 and 0.01 micrometer can be attained.

4. Environmental cleanliness of ultra-high-precision machining

A dust particle with a diameter of 0.3 micrometer may cause scraping because of judgment error of an operator or an inspector. When air-lubricated bearings or other precision bearings are assembled in a room whose air has not been cleaned, foreign dust may be responsible for surface roughness of a workpiece. As in the case of a microfine machine shop, environmental cleaning should also be conducted for ultra-high-precision machining or assembly shop. In an ultra-high-precision machine shop, the number of dust particles with diameter greater than 0.3 micrometer per cubic meter of air should be less than 10^2 (on the order of 100). At present requirements have been increased by an order of 10 and particle size has been reduced from 0.3 to 0.1 micrometer. In order to obtain such a highly cleaned environment, level by level cleaning should be applied, in other words, from landscaping outside the factory grounds to purification of corridors and the preparation rooms, down to the cleanliness of operational shops and machine tools. The atmospheric pressure of the clean shop should be slightly higher than outdoors; upon entering the shop, operators should be treated as per cleaning requirements.

5. Error compensation techniques

On the basis of overall error on-line inspection, the error compensation technique involves error data treatment (to find the repetition cycle) and to establish a mathematical model of the error with computer processing and monitoring for error compensation. The various effective factors having a bearing on the overall error can be neglected. In some countries, major advances have been made in error compensation techniques. For example, in a United States university the roundness has been reduced from 0.74 to 0.375 micrometer in overall machining of

outer-circle workpieces. Many tasks were also performed in China in this approach; in Jiaotong University in Shanghai, compensatory machining was carried out during the grinding of outer-circle of workpieces and grinding of linear guide rails; the workpiece roundness reached 0.079 micrometer, and the guide rail linearity was improved from the range between 3-4 micrometers for 320-mm long guide rails to 1 micrometer. At the National Defense University of Science and Technology in Changsha, roundness and linearity compensation techniques were adopted in precision machining; the roundness of the workpieces was up to 0.05 micrometer, and linearity of the workpiece base line was up to 0.5 micrometer for a 160-mm long workpiece. In progress made in error compensation techniques, a key problem is to seek precise, sensitive, and steadily reliable sensors and final controlling elements. Only with enhancement of the resolving power, response frequency, displacement range, and repeatability precision of sensors and final controlling elements, can the error compensation techniques^{be applied} in machining at even higher precision. Some other researchers state that, when considering the application of error compensation based on analyzing the factors of machine tool error in designing machine tools and instruments, there should be flexibility in machine tools and instruments; this is also a direction of progress.

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